THE SIMULATION OF ASTROPARTICLE EXPERIMENTS AND THE GEANT4 TOOLKIT

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ABSTRACT

The new generation of astroparticle experiments will use technologies common to High Energy Physics. Among such technologies a central place is given to the role of simulation.

1   Introduction

Monte Carlo simulation is nowadays an essential tool in the project of experiments. It is so common for physicists that one could think that such a technique is in use since ages; but indeed it is quite young, around 50 years. It was suggested by Ulam and von Neumann [1] in 1947 and first used for particle transport by Wilson [2], in the context of the the problem of electromagnetic showers. Such a problem had an elegant solution by Rossi and Greisen [3], although based on approximations valid beyond energies of a few MeV.

To solve the integro-differential equations of showers in lead, Wilson in 1952 uses the following procedure.

"The procedure used was a simple graphical and mechanical one. The distance into the lead was broken into intervals of one-fifth of a radiation length (about 1 mm). The electrons or photons were followed through successive intervals and their fate in passing through a given interval was decided by spinning a wheel of chance; the fate being read from one of a family of curves drawn on a cylinder (...) A word about the wheel of chance. The cylinder, 4 in. outside diameter by 12 in. long is driven by a high speed motor geared down by a ratio 20 to 1. The motor armature is heavier than the cylinder and determines where the cylinder stops. The motor was observed to stop at random and, in so far as the cylinder is concerned, its randomness is multiplied by the gear ratio (...)"

What are the requirements of a general-purpose simulation software for particle transport? To start, one has to take care in an adequate way of the physics, i.e., of the interactions: both for what is related to the probability of occurrence (i.e., to the cross section) and to the modelling of the final state. The physics of electromagnetic interactions is based on QED, and thus it is in principle well known. Electromagnetic interactions should be well modelled down to low energies (how low depends on the geometry and on the physics of the detector). The theory of hadronic interactions, QCD, is not in a status comparable with QED; as a consequence the simulations of hadronic interactions relies in general on QCD-inspired models rather than on the theory itself, and in general a reasonable simulation of hadronic interactions is good enough.

For a software to be used in the context of detector project and data analysis, however, the physics requirements are not the full story, and maybe they are not even the most important part. Technical requirements rely mostly on a well written code, with characteristics of

- modularity;

- easiness to add different generators;

- easiness to add new physics routines;

- friendly interfaces;

- good documentation;

- maintenability;

- support on different platforms;

- last but not least, a term taken from industry: customer care.

2   The shop-list before Geant4

Most of the large experiments '90s were basing their simulation on the Geant3 [4] package. The Geant3 code comes from a long program of development based at CERN between 1982 and 1994. Geant3 is written in FORTRAN; among his strong points, compared to the other simulations, are user-friendly packages for geometry description and visualization, and an overall easiness-of-use. Geant3 has proprietary routines for electromagnetic physics, and can bind several hadronic codes (GHEISHA is the most common).

However, a different package was and still is the reference for electromagnetic physics: EGS [5], a package which had a very long development and debugging at SLAC, LNL and KEK in the period between 1966 and 1985. EGS, presently at the version 4 (EGS4), is still the reference now for dosimetry, where definetly one should not be wrong. EGS4 has proprietary routines for electromagnetic physics; it is most commonly used in couple with FLUKA for hadronic interactions. EGS4 is written in MORTRAN, a pre-processor of FORTRAN, although several FORTRAN and C++ versions circulate on the Web. The code is overall a bit unfriendly: the geometry is difficult to define (it must be put in by means of a subroutine); few facilities, in particular for visualization, are available. The cross sections are computed by an offline preprocessor, PEGS, which must be run separately.

Besides Geant3 and EGS4, very little room was available for other products (DELSIM, GISMO etc.); and the success of a simulation code is boosted by the widespread use (which guarantees updating, debugging, availability on different platforms, interfaces).

3   The Geant4 toolkit

At the end of the '90s most of the simulation programs in High Energy Physics were based on Geant3. Several reasons however pushed the community to start a new project, aimed to improve Geant3. Among such reasons:

- limitations of Geant3 maintenance; in particular, because of too complex

structure driven by historical reasons, it was almost impossible to add a new feature or to hunt a bug;

- limitation of FORTRAN, and choice of object orientation and C++ by the physics community;

- shortage of man power at CERN;

- limitation of "central center" supports.

Such reasons convinced a group of physicists and computer scientists at CERN to start a world-wide collaboration for a new simulation project. Such a project was based on the most recent software engineering methodologies and, from an organizational point of view, on a world-wide collaboration.

3.1 Geant4: philosophy, history, future

Geant4 aims to be the successor of Geant3 by redesigning a major package of CERN software for the next generation of HEP experiments using an Object Oriented philosophy. The final aim of the project is to build a simulation more precise than EGS, and more friendly than Geant3.

A variety of new requirements also came from heavy ion physics, CP violation physics, cosmic ray physics, medical applications and space science applications In order to meet such requirements, a large degree of functionality and flexibility are provided: Geant4 is not only for High Energy Physics.

The main steps of the history of Geant4 are, for the time being:

Dec 94 Project starts

Apr 97 First alpha release

 Jul 98 First beta release

Dec 98 Release 0.0

Jun 01 Release 3.2 (with a complete list of physics processes)

Maintainment and upgrade are expected for at least 10 years; development is continuous, with two major releases each year plus a monthly internal tag (frequent bug fixes, new features, new examples).

Geant4 is presently based on more than 700,000 lines of code.

For more details on the collaboration and an updated status, see the very well done and maintained web pages [6].

3.2   The physics of Geant4

The library proposes several models for the most important interactions of particles with matter.

In particular for electromagnetic interactions one can use a "standard" package with at least all the features of Geant3, or call a package specialized in the low energy part (which aims to an accurate modelling of physics down to 250 eV and below, based on an important use of experimental tables). On the other direction Geant4 should be able to reproduce interactions up to the PeV and beyond: Geant4 is developed by people involved in fields other than High Energy Physics (e.g. medical physics, astroparticle physics).

All processes are already at least at level of Geant3, and in addition there are new processes (transition radiation, optical processes) and substantial improvements have been done in particular on the multiple scattering (new model, without path length restriction and with lateral displacement), on energy loss and on hard processes: in the future also the photoproduction of hadronic resonances will be modelled.

The electromagnetic processes are going through extensive tests, comparing both with data and with Geant3-based and EGS4-based simulations. Very good agreement with the data is seen on the simulation of electromagnetic showers.

For what is related to hadronic interactions one can bind GHEISHA, but more performant models have just been released for the Geant4 code and are under test. There is a large variety of models according to the energy, including string models (Geant4 is interfaced with Pythia7 for hard scattering), cascade models, evaporation and break-up.

In any case Geant4 is an open system to new inputs: the framework is such that different models can be easily integrated.

3.2.1   Confrontation with data

Facing such a huge development effort, debugging and tests is a major enterprise.

Fortunately, the distributed organization helps in boosting the manpower. Many comparisons have been done, and results published; a lot more are ongoing or starting within the collaborations using Geant4, in particular the LHC collaborations (ATLAS, CMS, LHCb, ALICE), BaBar (migrating from Geant3) and GLAST.

Again the most important results are summarized in the Geant4 web page.

3.3 Miscellaneous features

Geant4 includes several features goring in the direction of functionality and easiness of use; many such features come from comments originated from Geant3 users.

In particular such improvements affect the definition of cutoffs, geometry and utilities, hits and digitizations, fast simulation, visualization.

3.3.1 Cutoffs

Contrary to what done in Geant3, cuts in Geant4 are done in range rather than energy. It makes poor sense to use the energy cutoff: for example the range of a10 keV gamma in Si is a few cm, while the range of 10 keV electron is a few micron.

This modification causes a significant gain in results quality versus CPU usage; however, users can override the default and impose a cut in energy, track length, or time-of-flight. Physics processes can also ask to override the default when they need to (for example for a better treatment of boundary effects).

3.3.2 Geometry

Like in the philosophy of Geant3, Geant4 pre-defines basic geometries. The user can build new solids from union, intersection, subtraction of two solids (boolean solids) plus a transformation.

A utility *g3tog4* is provided to convert a Geant3 geometry into Geant4.

An interface with XML is in progress.

3.3.3   Hits and digits

Each logical volume can have a pointer to a sensitive detector; a hit is a snapshot of the physical interaction of a track or an accumulation of interactions of tracks in the sensitive detector.

A sensitive detector creates hit(s) using the information given in a tracking step; the user has to provide his/her own implementation of the detector response. A digitization is created with one or more hits and/or other digits by an explicit implementation by the user.

3.3.4   Fast simulation

Geant4 allows to perform full simulation and fast simulation (based on shower parametrizations, less accurate cutoffs etc.) in the same environment. The fast simulation produces the same objects as the full simulation (tracks, clusters etc.)

The full design is such to guarantee flexibility: the user can activate fast/full simulation by detector and/or by particle type, and use parallel geometries.

3.3.5   Visualization

Geant4 provides interfaces to graphics drivers (DAWN, RayTracer, OPACS, OpenGL, OpenInventor, VRML) such that one can visualize detector, hits and trajectories.

3.4   Things one has to do to run Geant4

Documentation (Getting started and installation guide, User guide for application and toolkit developer Software and physics reference manuals) is available at the Geant4 web site.

For many users, however, starting from the study of a manual is not the most effective way. For such users examples are provided: they can go to the Geant4 Web site, run an example and see how it is done.

Six novice examples are available with simple detectors and different experiment types to demonstrate the essential capabilities of Geant4: transport of a non-interacting particle through a slab, track in a simplified tracking detector,

electromagnetic shower (full), particle collision, parametrised electromagnetic shower, optical photon.

In addition advanced examples are available, two of which are relevant for astroparticle:

- xray_telescope, illustrating an application for the study of the radiation background in a typical X-ray telescope;

- gammaray_telescope, illustrating a gamma satellite-based detector of the new generation, similar to AGILE and GLAST [7].

3.5   Experience with Geant4

The production release is in use by many experiments in High Energy Physics and Astroparticle and by groups involved in medical physics.

Thanks to the wide use, the Geant4 developers got feedback. The first results confirm some of the Geant4 strengths in performance, simplicity of use, electromagnetic physics.

Benchmarks between Geant3 and Geant4 in electromagnetic showers demonstrate that Geant4 gives better physics at the same speed (and better speed for same physics).

The tests evidence also some weaknesses; reaction is fast.

4   The simulation of GLAST

An example of implementation for space applications is the simulation of the GLAST gamma-ray telescope [8].

GLAST has a wide range of physics objectives, from gamma astrophysics to fundamental physics. Correspondingly, the simulation should have an easy interface to the simulation of different sources, and be adequate both for the design and the physics analysis.

In addition, the gamma simulation in the tracker and in the calorimeter needs different details, and in particular a fast simulation should be available for the huge hadron background.

The GLAST simulation has been done, from the beginning, using C++ and with OO technologies in mind (GISMO was the choice, also because no other candidate present at that moment apart from standard FORTRAN simulations).

The migration of the GLAST simulation to Geant4 is now almost complete; it uses a prototype of the XML interface for geometry description.

5 Conclusions

Geant4 has demonstrated to be suitable as a Monte Carlo toolkit, in particular for applications in astroparticle physics and High Energy Physics. Among its strong points are the open structure (making it easy to integrate with specialized software) and the easiness of use.

The communities of astroparticle physics and High Energy Physics are quickly acquiring a good experience, and the validation with data, formulae and standard simulations is progressing fast.

In conclusion, Geant4 is becoming the standard *de facto* both for the simulation of detectors and for particle and radiation transport.

Acknowledgements

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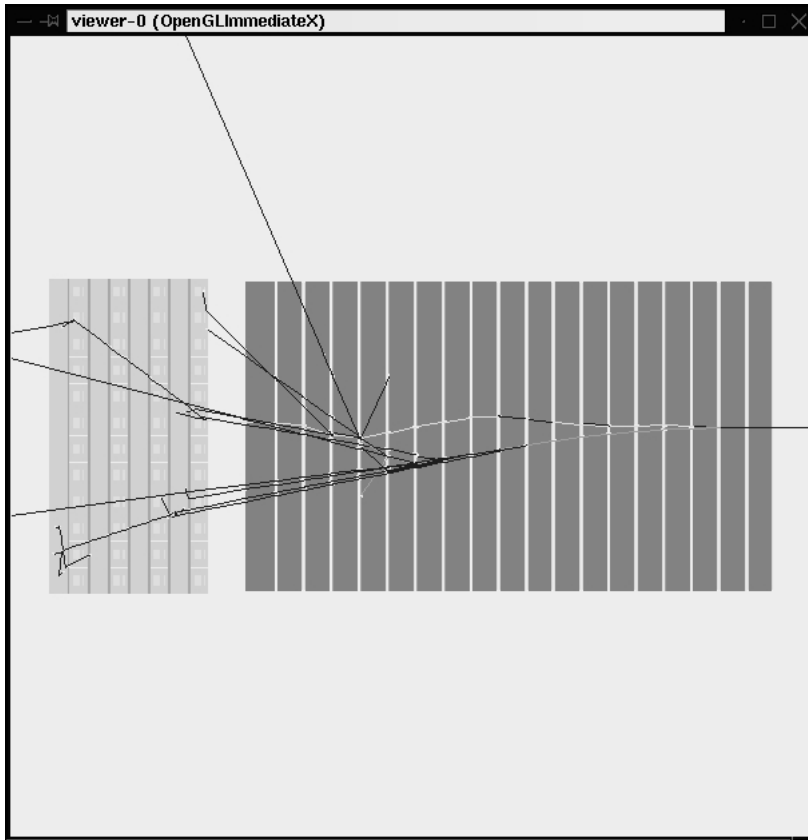
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Figure 1: *Display of the interaction of a gamma ray with the detector in the Geant4 simulation of GLAST.*